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THE RHONE RIVER DELTA

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Table of Contents

	page
Introduction	2
Acknowledgments	4
Field Work	4
Physiography	
1. Temperature	5
2. Winds	7
3. Precipitation	7
4. Evaporation	9
5. Marine currents and waves	10
6. Discharge of the Rhone	10
7. Salinity of the delta environment	12
a) The Rhone	12
b) Marshes	13
c) Coastal lakes	15
d) Golfe du Lion	17
Sediments	
Transport	18
1. Transport and sedimentation by fluviatile water currents	18
2. Transport and sorting in the direction of wave movement	20
3. Longshore transport by waves	20
4. Aeolian transport	21
Sources of sediment	21
1. Fluviatile supply from the drainage area	21
2. Fluviatile reworking of older deposits underlying the Recent delta	22
3. Marine reworking of older deposits underlying the Recent delta	22
4. Marine supply of sediments	22
Stratigraphy of Recent Deposits	
1. Basement of the delta	23
2. Thickness of Recent delta deposits	23
3. Summary of the depositional sequence in the inshore part of the delta	24

Influence of Relative Sea Level Movements on the Depositional Sequence 26

a) Rise in sea level 27
b) Subsidence of sea level 27
c) Stable sea level 28

Morphology of the Environments of Deposition 28

Fluviatile environments

a) Distributary channels 28
(1) The Grand Rhone 29
(2) The Petit Rhone 30
(3) The ancient channels 31
b) Point bars 37
c) Natural levees 37
d) Crevasses 38
(1) Crevasse channels 38
(2) Crevasse tongues 39
e) Fluvioaeolian dunes 39
f) Basins
(1) Central basins 40
(2) Delta flank basins 40

Coastal environments

a) Beaches 41
(1) Beach accretion by fluviatile supply 44
(2) Beach accretion by marine supply 48
b) Abandoned coastal ridges 49
c) Coastal basins
(1) Lagoons 52
(2) Coastal lakes 52
d) Submarine delta slope 54
(1) Fluviomarine environment 56
(2) Purely marine environment 56
(3) Bay environment 57
e) Continental shelf to the deep sea fan 57

Extension dans le Golfe de Fos 59

Management of the Rhone 60

Vocabulary 64

Bibliography 65

Map of the Delta

Figures | page

#1	Mean monthly air temperatures (1936-1943) at Arles and Salin de Giraud showing maximum, average, and minimum temperatures.	6
#2	Mean monthly precipitation at Sète and Salin de Giraud.	9
#3	Difference between monthly evaporation and precipitation at Salin de Giraud.	9
#4	Average monthly level of the Rhone at Beaucaire (1877-1916).	11
#5	Distribution of fresh and saline environments in the terrestial delta.	14
#6	Isopach map of the Recent delta deposits.	24
#7	Nomenclature of active and abandoned Rhone channels.	31
#8	Delta advance as related to channel changes during the last 5,500 years.	34
#9	Advancing and rededing shores of the Rhone delta.	41
#10	Development of the present mouth of the Grand Rhone since 1841.	45
#11	The Golfe du Lion.	55
#12	Section through the Recent delta deposits.	55
#13	Sections of the submarine slope of the Rhone delta.	57
#14	Plan for the management of the Rhone from Switzerland to the sea.	61

Photos page

#1	The mouth of the Grand Rhone.	1
#2	The city of Arles.	3
#3	Ile des Pilotes looking west.	8
#4	The salt reserve near Salin de Giraud.	17
#5	A saltern of Cie. Salinière de la Camargue.	18
#6	Patterns in beach sand due to differential cementation by $CaCO_3$.	43
#7	Beach ridge at the waterline, looking west from a point 3 km. west of Grau de Roustan.	44
#8	Grau du Piémanson looking southwest from the Grand Rhone.	46
#9	Grau de Levant, looking east from a point 1 km. west of its mouth.	46
#10	A temporarily flooded basin and a permanently flooded one.	53
#11	A rarely flooded basin near Etang de Fournelet.	54
#12	Gravels dredged from the Golfe de Fos.	60

Photo #1 The mouth of the Grand
Rhone (looking southeast from a
point immediately west of the
mouth).

Introduction

A large part of the clastic sediments occuring in the stratigraphic column have been deposited in deltaic environments; partly as fluviatile top-set beds, but the majority probably as marine fore and bottom set beds (van Andel, 1955). For this reason, a thorough knowledge of deltaic environments is vital if a geologist expects to understand facies.

The Rhone River Delta covers a large part of the Golfe du Lion and projects southward into the Mediterranean over a nearly horizontal shelf to a depth of 90-100 meters below sea level. The continental slope and deep sea fan separate the shelf from the Mediterranean basin (Figure #11, page 55).

To the east the deltaic beach coast merges abruptly with the rocky coastline east of Fos. To the west the beach extends to Cap Bear. In the north, the delta is bounded by the Plaine de la Crau to the east and the Costière to the west, forming what appears to be a classical triangular shaped delta with a little more than 700 square miles of surface area. (see the enclosed map of the Rhone Delta- after Kruit, 1955)

The lower course of the Rhone River flows approximately north-south and bifurcates near the ancient Roman city of Arles into two distributaries: the Grand Rhone, which flows southeast, and the Petit Rhone, which flows southwest (Photo #2 The city of Arles, page 3). They flow over the delta surface, called the Camargue, and enter the Golfe du Lion.

The delta was inhabited succesively by Greek and Roman cultures. They found the natural levees favorable for the growing of grain, fruit trees, grapes, and rice. Man has altered the course of delta growth and change by his desire that the river should serve him. Specific instances will be brought out later.

The purpose of this senior thesis is to present a general discription of the Rhone River Delta with emphasis on morphology of the environments of deposition. I plan to combine the findings of previous studies with my own in hopes of presenting an up-to-date analysis of the delta's development- past, present, and future.

Photo #2 The city of Arles. In the center of the photo is a coliseum where many a Christian met his fate in the jaws of a lion.

Acknowledgments

I wish to express my graditude to the people here and abroad who spent their time and patience guiding me and so enabling me to write this thesis. First and foremost, I thank Mr. Richard J. Anderson of Battelle Memorial Institute for the inspiration and foresight that went into this paper's planning. He continually gives of himself and his busy schedule to help me whenever I need advice. I also thank the staff of several organizations in France: L'Institute d'Océanographie at Marseille, La Compagnie Nationale du Rhone in Avignon, and the Port Autonome de Marseilles at Marseille. They spent many hours answering questions in spite of my poor accent. I want to thank my professors at Ohio State University for all the help that they have given, making it possible for me to become a geologist.

Field Work

Two and one half months were spent researching in the delta region, from January to March, 1969. While in Europe, data was obtained by various methods:

1) Library research- Several excellant papers were read by this author before going to the delta proper, that he might have a better background of the situation.
2) Personal communications- Because no major studies have been carried out in the last 15 years, it was necessary to contact several organizations for up to date data on the delta's development.
3) Direct observation- This author lived on the delta for

two weeks at Port St. Louis and also made several trips to parts of the delta at other times. The southeast section of the delta surface was well covered on foot. 150 surface samples and many photographs were taken and are stored at the author's residence for later analysis. The author will forgo a detailed study of grain size and mineralogy at this time with the idea of using the analyses for a later thesis.

4) Aerial photos- Aerial photos were taken by this author in order that the changes and the relationships of delta environments might be better observed.

5) Marine samples- Marine samples were taken with a very simple cone shaped device which had only to be ~~drag on~~ dragged along the bottom. These samples are also at the author's residence.

Physiography

1. Temperature-

A detailed study on air temperature has been made by Schachter (1950). Figure 1 (page 6) is a summary of the mean monthly air temperature at Arles and Salin de Giraud showing the maximum, average, and minimim temperature from 1936 to 1943. The graph indicates a decrease in air temperature from north to south on the delta surface.

Schachter (1950) also studied water temperature in the delta's basins and showed that the air temperature

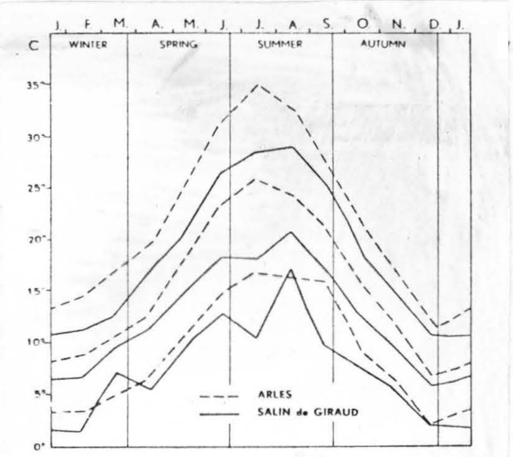


Figure #1 Mean monthly air temperatures (1936-1943) at Arles and Salin de Giraud showing maximum, average, and minimum temperatures (after Schachter, 1950).

corresponds approximately with the water temperature but the air temperature was slightly lower from December to April and slightly higher the rest of the year.

Rouch (1941) has studied the average monthly temperature of the surface water off Monaco and Marseille. He recorded an average maximum of 22°C. in Marseille in August and an average minimum of 12°C. in February.

The variations of temperature with depth in the Mediterranean has also been studied by Rouch (1941). These data show that the temperature is approximately 13°C. between depths of 100 meters and the 2000 meter level in the N.W. Mediterranean at all times of the year. In the summer, the temperature will rise as one goes from the 100 meter level to the surface, but in the winter it is approximately 13°C. at all depths. This constancy of temperature makes the Mediterranean an interesting place to study the distribution of benthonic microfauna. However this is not within the scope of the present study.

2. Winds-

The direction and average force of wind is responsible for the aeolian transport of sediment and for the generation of waves and currents which are also sediment transporters.

The annual distribution of winds at Sète is shown on the enclosed map. Sète is located 70 kilometers from the central delta (Instructions Nautiques, 1948). When the prevailing northwest wind is strong, it is called the "mistral." It is a dry wind and an important control on evaporation in the Rhone Delta's region. The mistral can attain speeds of 150 kilometers per hour. (Kruit and Duboul-Razavet, 1957). The farmers of the region plant trees in rows perpendicular to the direction of the mistral to keep their land in place (Photo #3 Ile des Pilotes, page 8). The other northerly winds are also dry and of moderate force. The "marin" from the southeast is the dominant onshore wind. It is most frequent in autumn and winter and causes rainfall on the delta. Easterly winds are only important in the spring.

3. Precipitation-

Precipitation is one of the factors that controls salinity on the delta surface. In the drainage area of the Rhone, the precipitation decreases from north to south (C. Kruit, 1955). In the northern drainage area the rain is brought by oceanic western winds that passed the northern

Photo #3 Ile des Pilotes looking west. The ground water here is fresh so fruit trees can be grown on the island. The larger trees are used to slow down the force of the mistral. Nóte also the craft in the southeast corner of the photograph. It is called an automoteur and is used to carry petroleum, salt, and general mèrchandise on the river. Its capacity is 500 to 900 tons depending on the depth of the Rhone.

border of the central plateau. In the southern part of the Rhone valley, the amount of rainfall is dependent on Mediterranean winds. The mean monthly precipitation at Sète and Salin de Giraud is shown here in Figure #2 (page 9) (after Schachter, 1950; Instructions Nautiques, 1948). The total annual precipitation in the delta area ranges between 350 and 600 mm. (C. Kruit, 1955). The summer is the dry season; the autumn is the main rainy season, which causes flooding of the low lands of the delta region.

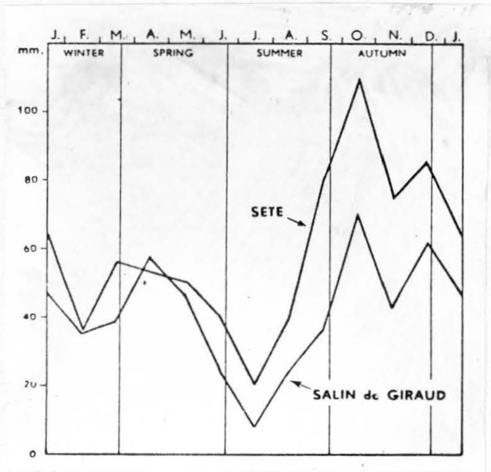


Figure #2 Mean monthly precipitation at Sète and Salin de Giraud (data from Schachter, 1950; Instructions Nautiques, 1948).

4. Evaporation-

Evaporation is also a factor that affects salinity on the delta. It is greatest in the summer when the dry mistral is blowing and the temperatures are the highest. Figure #3 (page 9) shows the relationship between evaporation and precipitation at Salin de Giraud.

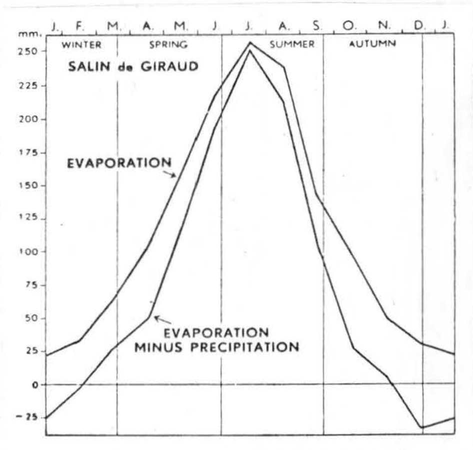


Figure #3 Difference between monthly evaporation and precipitation at Salin de Giraud (after Schachter, 1950).

The diagram illustrates that the amount of evaporation outweighs the amount of precipitation, which makes the delta a convenient locale for the exploitation of salterns.

5. Marine currents and waves-

The currents in the Golfe du Lion vary with the force and direction of the wind. The combination of the mistral and the Coriolis force cause a predominant wind-drifted current to the southwest. The dominant onshore wind produces waves approaching from the southeast. The direction of wave propagation is of importance in sediment transport along the beach. The longshore currents are generally westward along the delta but a longshore current has been noted going eastward along La Gracieuse (Mr. Izaute, personal communication), but this is explained by the relationship between the position of the spit and the direction of propagation of the waves.

The tidal currents are of little importance in the Mediterranean. The average difference between high tide and low tide at Marseille is 21 cm. (C. Kruit, 1955). The The fluctuations of sea level are controlled by the winds. The mistral may lower the sea level along the delta coast 0.5 meters; the onshore gale might raise the level 1.0 meter (C. Kruit, 1955).

6. Discharge of the Rhone-

The periodical variations in the water level of the Rhone determine the times in which sedimentation is active on the delta surface. Figure #4 (page 11) shows the

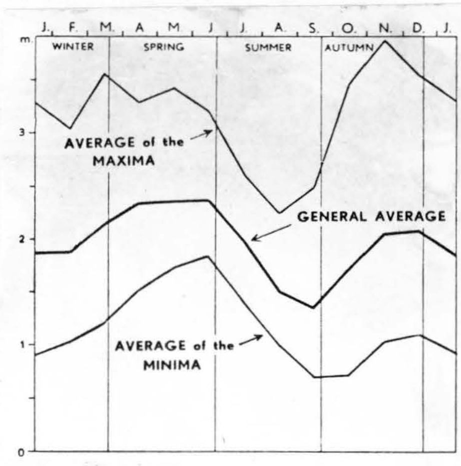


Figure #4 Average monthly level of the Rhone at Beaucaire (1877-1916) (after Parde, 1925).

average monthly level of the Rhone at Beaucaire from 1877 to 1916 (after Parde, 1925). Parde (1925) has discussed the variations in the discharge. From May to June, the melting of alpine snow accounts for the high Rhone level. In this period the discharge at Beaucaire varies from 1,500 to 2,500 m^3/second. The discharge gradually decreased to a low of 1,200 m^3/second in September. From October to December the discharge varies due to a high level of rainfall in the Rhone's drainage area. Since Roman times, deforestation and subsequent erosion has transformed the lower drainage area into a rocky landscape. After heavy rains, the water runs off the bare slopes causing sudden serious floods. Because of these factors, the maximum and minimum discharge have both been recorded at Beaucaire in Autumn. Poggi (1968) states that the important floods come in Autumn after sudden rain and discharges at Beaucaire can vary from 480 to 14,000 m^3/second. He also records the average annual discharge at Beaucaire as 1,460 m^3/second. From January to March, the discharge is due to northern oceanic supplies and occasional Mediterranean showers.

7. Salinity of the delta environment-

The classification of the salinity of the deltaic environments has been adopted from Redeke (1933):

	%Cl	Approximate salinity (%)
Sea water	17	35
Brackish water		
polyhaline	10-17	20-35
mesohaline	1-10	2-20
oligohaline	0.1-1	0.2-2
Fresh water	0.1	0.2

a) The Rhone- C. Kruit (1955) collected surface samples of the Grand Rhone near the mouth to test for degree of salinity. He found the surface water near the ferry at Salin de Giraud (Bac de Barcarin) almost fresh (salinity 0.5%). Samples taken nearer the mouth showed that a superficial layer of fresh water flows into the sea over a deeper saline layer. At a station 1.5 km. north of the mouth, the bottom water at 5.5 m. showed a salinity of 37% or near that of undiluted Mediterranean sea water. The surface water there was only slightly mesohaline (2.5%). At the mouth the surface water was a little more mesohaline (4%) due to some mixing with the deeper saline layer. The salt water current occasionally mounts as for north as Mas Thibert. This salt water is especially harmful for rice, fruit trees, and vinyards which are grown on the delta. Evaporation in the summer may reduce the depth of the fresh water layer to 50 cm. and occasionally, by mistake, fresh water is irrigated. If the discharge increases, the salt water is forced more out to sea; if the discharge decreases, the opposite will occur (Mr. Boniface, personal communication). A sand bar in front of the mouth of the Rhone, which varies in depth from 1 to 2 meters, restricts the saline water's circulation at times of low water level.

b) Marshes- C. Kruit (1955) has demonstrated that the salinity on the delta increases southward. The fluviatile basins in the northern part are fresh to mesohaline. In the southern delta the fresh to mesohaline environments occur in close association with distributary channels and are clearly marked by reed vegetation, which is absent in higher salinity environments. The high water level the first half of the year formerly provided an uninterrupted supply of fresh water to the basins which bordered active channels and the supply exceeded the rate of evaporation. In the summer, the salt content might have risen slightly, but in Autumn the Rhone floods apparently refreshed these basins (C. Kruit, 1955). The alternation between fresh and brackish conditions made it impossible for a sound distinction to be established between environments. However, now this distinction can be seen since the fresh water has been so well controlled by the construction of dikes, drainage channels, pumping stations, and irrigation systems. As one travels across the delta it is easy to establish exactly where one environment ends and the next begins (Figure #5, page 14). These present day restrictions on the free

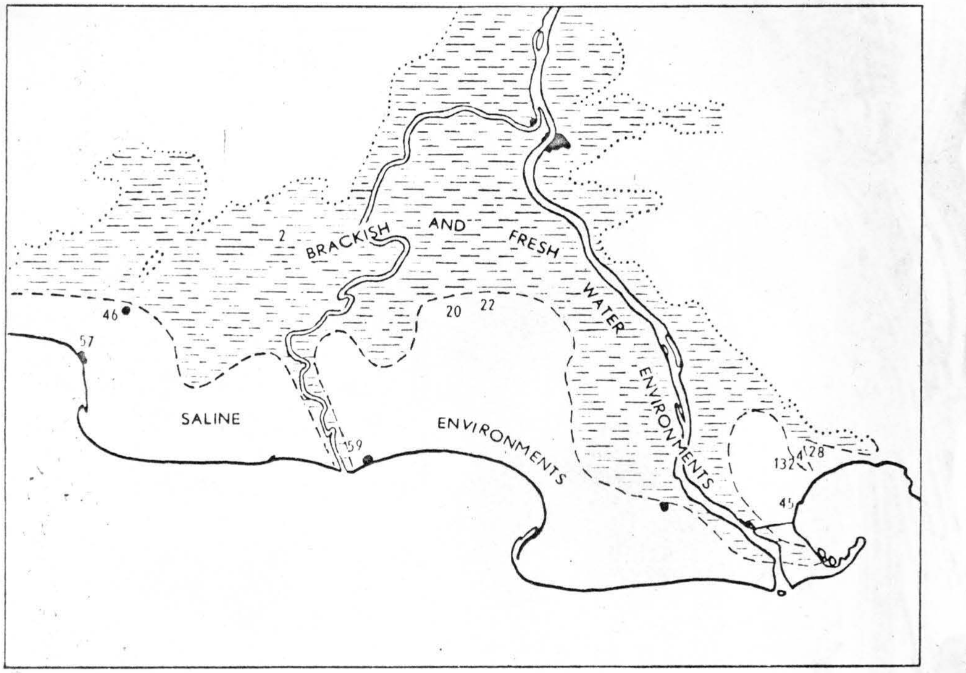


Figure #5 Distribution of fresh and saline environments in the terrestial delta (after Kruit, 1955).

interchange of the delta's waters ensure that the northern delta basins are fed only by precipitation and by the supply of slightly brackish irrigation water from the rice fields.

The bottoms of fresh to moderately brackish environments apper to consist everywhere of thick clayey deposits so that circulation in the deeper sand beds by salt water is prevented from influencing the upper sediments.

Natural levees are crossed by channels through which the northern basins may easily drain their surplus water to the southern basins.

c) Coastal lakes- The southern basins, especially those between ancient coastal ridges, are strongly saline in midsummer. The high salt content is due to high evaporation rates of water supplied from the sea. In the winter, the southern winds used to sweep water over the delta surface into marine basins. Nowdays this supply is restricted due to the construction of dikes between Stes. Maries and Salin de Giraud. The supply of ground water from the ocean is now the most important. The upper part of the Recent deposits in the southern delta are composed primarily of unconsolidated, rather coarse and permeable coastal sands (C. Kruit, 1955). There is no potable fresh water in the Recent delta deposits south of Etang de Vaccarès. Inhabitants of this region must drain fresh water from the Rhone distributaries or collect rain water.

The high rate of evaporation has caused saline crusts to form on the delta surface, even on elevated areas such as levees. The southern basins are very saline in summer and some dry up leaving a thin crust of salt. This salt crust was noticed bordering most of the southern lakes where the water level was low due to daily changes in weather and water supply.

In the spring and autumn, the basins used to be refilled with fresh water of fluvial origin, but this is now excluded due to flood control by the complex dike system. The alternation of salt water and strong evaporation on the delta causes winter salinity values of 20 to 30% and summer values higher than in any known normal marine environment. In August of 1950, the salt concentration in the southern basins averaged 45 to 60%, but extreme values such as 132% in Etang de la Roque did exist (C. Kruit, 1955).

The deeper basins with their bottoms below sea level are permanent lakes because of the supply of ground water. In the Etang de Vaccarès, the largest permanent lake in the central delta, the salinity is intermediate between the salinity of the northern fresh water marshes and the yearly salinity variation of the southern saline coastal lagoons and temporary lakes. The supply of slightly brackish water from the drainage channels aids in holding down the summer salinity values in the southern lakes. Long continuing mistrals may flood the southern coast of the Etang de Vaccarès with less saline water but the evaporation rate quickly nullifies any refreshening. No accurate measurements have been made on the effect of the Rhone's discharge on the salinity of the region.

The salt industry has created many artificial saline lakes by flooding a number of natural basins. All of the larger permanently flooded basins of the

Ile du Plan du Bourg are controlled by Cie. Salinière de la Camargue. An engineer said that this company produces 1,000,000 tons of salt a year. Photo #4 (page 17) is an aerial view of the salt just south of Salin de Giraud. Photo #5 (page 18) is looking south from a point just south of the salt in Photo #4. It shows the artificial basins which are flooded with sea water and then left to evaporate. Then the salt layer is scraped off and added to the great reserve shown in Photo #4. The complex south of Salin de Giraud is the largest on the selta and they are presently planning to expand westward.

d) Golfe du Lion- The average salinity of the Mediterranean is about 38%. The discharge of the Rhone's fresh water is bound to affect the salinity of the Golfe du Lion in the region of the delta but accurate measurements are unavailable.

Photo #4 The salt reserve near Salin de Giraud.

Photo #5 A saltern of Cie.
Salinière de la Camargue
(looking south).

Sediments

Transport- In a delta, water is the most important transporting agent. A distinction must be made between wave transported sediments and water current transport. Each will influence sorting differently.

1. Transport and sedimentation by fluviatile water currents-

In the river channels, the transport of clastic sediments is variable according to size of grains. The coarsest particles will move by rolling; the medium grades by saltation; the finest in suspension. Therefore, the sediments are already sorted to some degree and increase in size with depth.

The heavier particles may move only in times of flood. In meander belts, the channel cuts on the outer bend and deposits coarse sediment on the inside bend. The sediments deposited are left until they are eroded when a new meander develops. This sediment moves in slow shifts downstream.

The situation is much different for the transport of the suspended sediment. During times when there is no flooding, the sediment is carried to the sea. When flooding occurs, the water with the suspended sediment overflows the natural levees. The flow is less turbulent over the banks than in the channel, and the coarser sediment is quickly deposited, building up the natural levees. As the flow moves further from the river, increasingly finer sediment is deposited. Very small and slow inundations will leave the finest sediments on the natural levees, while greater and quicker inundations leave silt and fine sands on the levees while finer grades move to the basins. Thus natural levees can vary from fine sands to clay while the basins will be entirely of clay. With the advent of dikes to control flooding, deposition by inundation is rare on the Rhone delta. The sediment is all carried to the sea and unless subsidence or a rise in sea level occurs, there will be little deposition by fluviatile flooding on the delta in the future.

Sorting in fluviatile sediments is generally poor when compared to marine sediments. The reason is that sediment transfer is spasmodic on the delta and water currents vary greatly in strength. In the sea, the currents are more constant but do vary in strength and direction depending on the wind. This constancy of flow is most important in determining the degree of sorting, thus marine sediment is more uniform in size.

2. Transport and sorting in the direction of wave movement-

Beach sands are rarely dispersed into deep water, and even if the coast is subject to erosion, the bulk of beach sands never crosses the 8 meter depth contour (C. Kruit, 1955). The swash and backwash of the waves is the type which continually drive the eroded sands toward the shore and sands are carried away by longshore currents.

With increasing depth the velocity of the water will fall below that necessary to transport each grade size. When the different sizes settle to a depth where the velocity is too low for transport, they will be deposited. Turbulence upward may counteract much of the settling velocity. The silt and clay sizes are sorted out of the high turbulence zone and deposited in deeper water. Sorting then, is dependent on the relationship between the settling velocity and the eroding velocity of each grade size to the velocity of the water at any given depth. Annual variations in wave size will alter the depth at which the different size grades are deposited.

3. Longshore transport by waves- When waves approach the shore at an oblique angle, longshore transport will arise parallel to the shoreline. The direction of transport will depend on the direction of the strongest onshore wind. In the case of the Rhone River Delta the strongest onshore wind is the marin from the southeast.

The progression of the erosion of abandoned subdeltas shows that longshore transport is confined predominantly to the surf zone and the distribution of marine sediments confirms this (C. Kruit, 1955).

4. Aeolian transport- With the advent of flood control, aeolian transport has become more important. Much of the delta has plant cover, but in the southern delta, where salinity is high and plant cover low, wind erosion is quite effective. It strips the mud cracked salt flats of sand and silt and many dunes are produced. They line the beaches and also are present on old coastal ridges that are being reworked. The wind has also created dunes from point bars, west of Arles.

Sources of sediment- The different sources must be considered that have supplied the construction materials for the Rhone River Delta.

1. Fluviatile supply from the drainage area- The drainage area of the Rhone is 1.2×10^5 km^2. (Menend, 1965), and one would expect that most of the sediments of the delta have been supplied from this drainage basin. Van Andel (1955) found that the average annual sediment load was $2.6 \times 10^{-2} km^3$. The deposition of fluviatile sediments in the past has been greater in the marine environment than on the delta surface, but as previously stated, the present deposition is restricted to the marine environment. Van Andel's (1955) heavy mineral investigation showed that all Recent sandy deposits of the delta belong uniformly to the Rhone province.

2. Fluviatile reworking of older deposits underlying the Recent delta- Pliocene and Pleistocene rocks are present in the basement of the delta and are exposed occasionally in the outer bend of a meander. Some Pleistocene rocks have been found just west of Mas d'Icard exposed in the channel bottom (C. Kruit, 1955). These sources are negligible when compared to the vast source of sediments of the drainage area.

3. Marine reworking of older deposits underlying the Recent delta- Gravel in considerable amounts can only be found in the beaches west of Aigues-Mortes and to the east near Fos. This gravel indicates marine reworking of Plio-Pleistocene deposits eroded by waves. The coastal ridges to the north of Aigues-Mortes show subsurface contact with the Pliocene of Mas Psalmody. The gravelly beach ridges in this area are situated mainly to the north and to the west of Aigues-Mortes, in approximate correspondence with the normal direction of coastal transport in this area (C. Kruit, 1955). The gravels in the beaches of Golfe de Fos, as well as the abandoned beaches in the area, are from the Pleistocene Crau which underlies the eastern delta.

4. Marine supply of sediments- If there are sediments present in the delta from marine supply, they would most likely be from the east because of the westward drift due to the winds and Coriolis force. However, the coastline east of Fos is very rocky and so supplies are limited. Van Andel's

(1955) heavy mineral study did not provide any evidence for the supply of sediment different from the normal Rhone load.

Stratigraphy of Recent Deposits

1. Basement of the delta- The basement of the delta is everywhere underlain by gravel deposits that dip approximately 1:1,000 south and emerge near the base of the submarine slope (Figure 12, page 55) (C. Kruit, 1955). Because they dip away from the river valley, and because of the incapacity of the sea to transport any coarse grained sediment to considerable depth, the gravels are of fluviatile origin and were probably deposited during Pleistocene glaciation. The source of these gravels could either be from Pleistocene gravel deposits of the Rhone Valley, or those of the Pleistocene Plaine de la Crau. The gravels of the Crau in the eastern delta dip in an unaltered way from the Plaine de la Crau surface to the basement of the Recent delta and the gravels are present under Port St. Louis at a depth of 30 meters (Figure 6, page 24).

2. Thickness of Recent delta deposits- Non-gravelly sands and muds wedge out rapidly to the north and south above the pre-Holocene surface. The thickest deposits appear to be along the present shoreline where they reach a depth of 60 to 70 meters (Figure 6, page 24). The thickness of fluviatile sediments in the northern delta is due to the

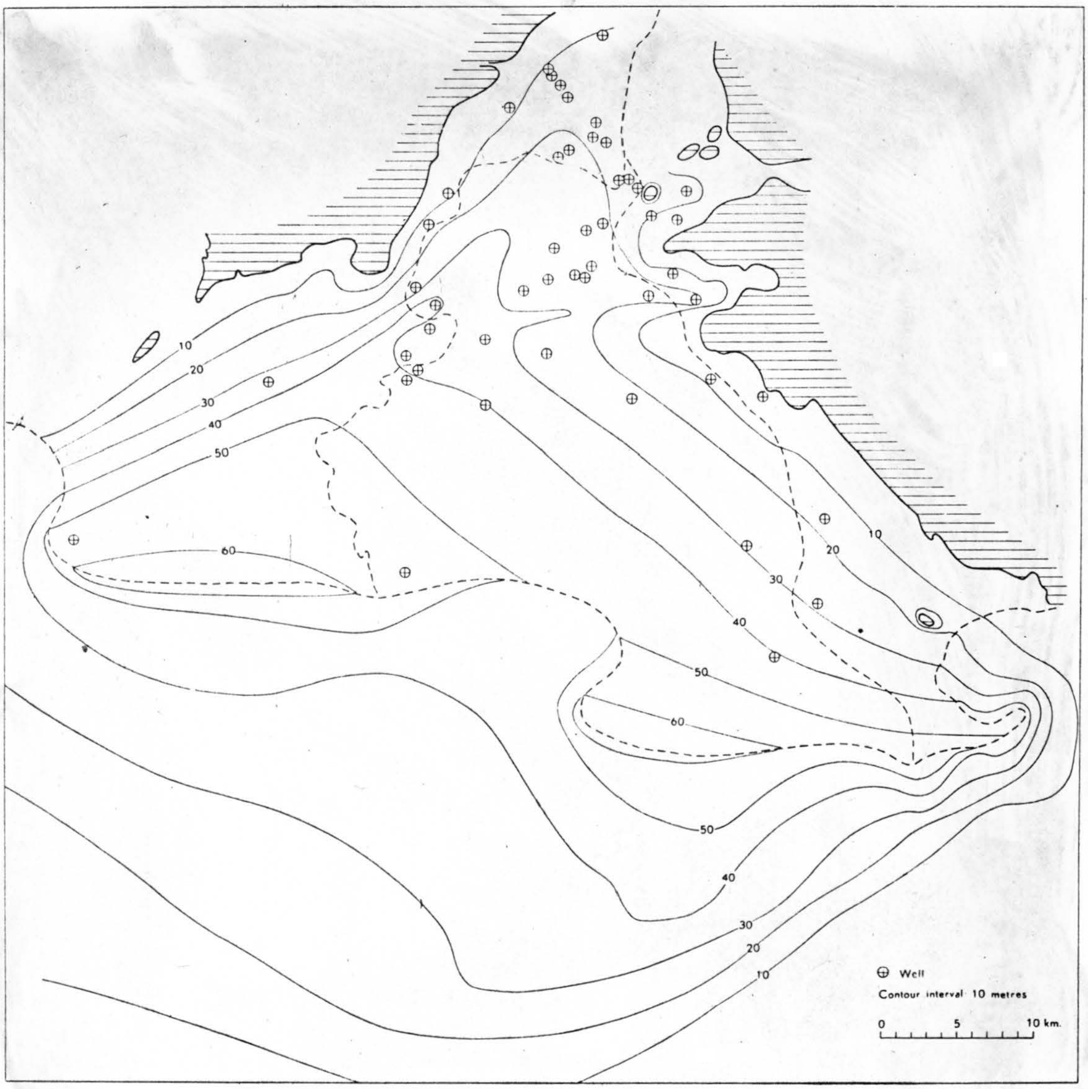


Figure #6 Isopach map of the Recent delta deposits (after C. Kruit, 1955).

post Pleistocene rise in sea level. To the north of Marais de la Grand Mar the sedimentary column was accumulated exclusively in environments belonging to the terrestrial delta while south of the marais marine beach and nearshore deposits are largely dominant (C. Kruit, 1955).

3. Summary of the depositional sequence in the inshore part of the delta (after Kruit, 1955)- The succession of depositionary events deduced from the study of the top 8 meters of sediment cover, in the subaerial part of the

delta, can be summarized as follows:

a) Coastal lake conditions in the northwestern area ("first coastal lake series").

b) Deposition of sandy and silty crevasse or natural levee sediments all over the northwestern area.

c) Return of coastal lake conditions in the northern area ("second coastal lake series").

d) Interruption of normal deposition of the second coastal lake series by the formation of a peat layer all over the northern and central areas. The formation of peat was preceded or followed by the formation of _Cardium_ beds (lower _Cardium_ and peat horizon).

e) Continuation of deposition of the second coastal lake series in the northern area. The position of the beachline may be indicated roughly by the present northern shore of Etang de Vaccarès. Natural levee deposits show the presence of a distributary channel near Domaine de Méjeanne. The coastal lake environment gradually recedes from the northern part of the delta and is succeeded there by the formation of clayey natural levee and marsh sediments. Crevassing occurs occasionally in the southern part of the basins, but the deposits are entirely reworked into sandy or silty coastal lake sediments.

f) The middle _Cardium_ and peat horizon was formed when coastal lake deposition had practically disappeared from the northern part of the delta.

g) Deposition of the second coastal lake series continued in the central area; fluviatile clayey deposition at first covered the whole northern part of the delta, but this deposition was suddenly replaced by the formation all over the northern area of fluviatile silty sandy deposits.

h) At many places in the central area the deposition of the second coastal lake series concluded with the formation of the upper Cardium horizon. In the southeastern area, however, the deposition of coastal lake sediments started (on top of a series of beach deposits) somewhat earlier than the formation of the upper Cardium horizon, and continued thereafter.

i) Marsh deposits are formed in the basins of the northern and central parts of the delta; coastal lake conditions have now moved to the southern part. Cardium beds are at present being formed in the coastal lake environment.

Influence of Relative Sea Level Movements on the Depositional Sequence

The formation of delta sediments is determined by the outline, relief, and climatological character of the drainage basin, but also the alterations in the relative level of the sea and delta surface. Both fluctuations in sea level and regional subsidence will influence the depositional history of the delta. There is worldwide evidence supporting a rise in sea level after the last Pleistocene glaciation. The Sylvé Godesque ridge is the position of the shoreline at the moment at which sea level reached approximately its present position, about 5,500 years ago (C. Kruit, 1955). All the sediments deposited since then have been deposited at sea level. The broad plain of beach sediments existing on the delta surface which correspond to the present sea level, indicate the insignificant influence of subsidence in the region (C. Kruit, 1955).

a) Rise in sea level- A quickly rising sea will lead to beach distruction and marine flooding of the delta. If the rise is slow, the receding beaches may be able to keep pace with the rise. The absence of real marine intercalations between the series of shallow coastal lake and fluviatile deposits in the northern part of the Rhone delta shows that apparently no real marine invasions have occured here behind the beach cordon (C. Kruit, 1955). The absence of large tides and the slowness of sea level rise in the region has favored the stability of the Rhone delta beaches. A rise in sea level will cause the Rhone floods to reach higher levels and the natural levees will grow accordingly.

b) Subsidence of sea level- A subsidence in sea level will cause the distributaries to lower and flooding will occur less frequently. The sea will also flood the delta less. If the supply of clastic sediment to the delta surface is reduced, organic debris may accumulate on the delta surface. The presence of peat and <u>Cardium</u> shells has proven to be a good indicator of an interruption in deposition, but these will also be present in times of stable sea level.

c) Stable sea level- When the sea level is stable the following events will take place: Coastal recession at river mouths will cease and the formation of subdeltas will commence, resulting in a southward extension of the delta surface. The deposition of sediments on the natural levees may continue for some time but will gradually decrease. The construction of dikes on the delta surface has restricted the chance of flooding immensely. Organic deposits are accumulating on the delta surface during the present period of sea level stability.

Morphology of the Environments of Deposition

There are two main divisions based on morphology possible on the delta. The first is the northern delta plain, enclosed between the Plaine de la Crau and the Costiere, consisting of fluviatile deposits. The second is the delta south of the Etang de Vaccares, where marine beach deposits dominate the delta surface, dissected by broad and narrow strips of fluviatile sediments, marking the present and previous outlets of the Rhone to the sea.

The fluviatile environments will be considered first.

a) Distributary channels- Two kilometers north of Arles, the Rhone bifurcates, forming the Petit Rhone which empties into the Golfe du Lion near Stes. Maries and the Grand Rhone which flows into the gulf near Port St. Louis. This area is regarded as the head of the delta as it is the place where the gradient declines considerably.

Between Lyon and Tarascon the river gradient averages 60 cm./km., below Arles it is 10 cm./km., and at the coast the gradient is only a few centimeters per kilometer (C. Kruit, 1955). The sharp change in gradient at the head of the delta makes that area the most likely to form crevasses.

(1) The Grand Rhone- The Grand Rhone is 150 meters wide at Arles, but when it swings southeast, just south of Arles, it becomes 400 meters wide.

The dissimilarity in the meander patterns of the upstream and downstream portions of the Grand Rhone below Arles is probably due to lithological differences in the composition of the strata in which the meanders have formed. The delta topography shows that previously well developed meanders were present in the lower course (Bras Mort, Bras de Fer), but were abandoned and are now marsh. The meanders in the upper Rhone have deviated very little in comparison, from their present paths.

The present day lower course between Salin de Giraud and the river mouth is not natural. During a flood in 1711 the river found a shorter outlet through an artificial canal that had not been locked properly. The mouth of the Grand Rhone has also been altered artificially and a discussion of this will be presented later.

The distributary channels contain coarse and poorly sorted sands. When silts and clays occur, it is thought that they are a result of a slack in discharge. At the mouth of the Grand Rhone, where the river widens and the water is moving slower, silts and clays were found on the surface of the channel bottom. In abandoned channels, coarser sands are overlain by finer ones due to the slack in discharge as the channel was abandoned.

Reed vegetation is an excellent trap for fine sediments. Reeds line the banks of fresh water channels, while just a short distance away, the salt environment is often present.

(2) The Petit Rhone- The Petit Rhone is composed of a number of channels of different age and origin (Figure #7, page 31). The Fourques channel has existed since the late Roman period and it was created after the artificial narrowing of the Grand Rhone between Arles and Trinquetaille caused the formation of a crevasse to the north of Arles. The southward turn of the Fourques channel was enforced by the hills near St. Gilles. The southwest channel from Albaron to Sylvéréal is the oldest channel section still active on the delta. The meanders in the Sylvereal channel are more advanced than those of the Fourques channel. These sharp bends have developed from the former broad bends of the old Albaron channel which carried the main discharge for some time. The Rhone d'Orgon is the youngest in the sequence and dates from 1552. It was artificially cut to provide fresh water to Stes. Maries. The Rhone d'Orgon flows between two former beaches which stand only one meter above sea level (C. Kruit, 1955). The sediment load of the Petit Rhone is not great enough to compensate for wave erosion and the Grau d'Orgon is receding. The original river plain of the Rhone d'Orgon was at one time

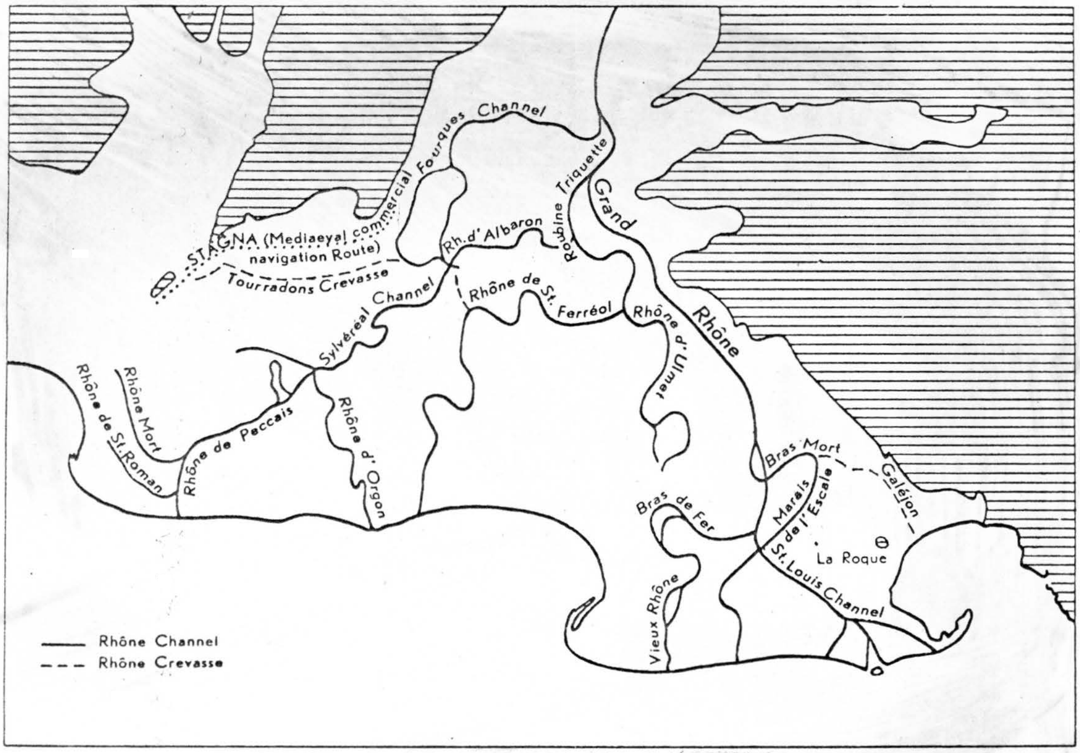


Figure #7 Nomenclature of active and abandoned Rhone channels- (The Petit Rhone is a combination of the Fourques channel plus the Sylvereal channel plus the Rhone d'Orgon.) (after C. Kruit, 1955)

below sea level like many other interstitial areas between former beaches. There are straight sections of the Rhone d'Orgon next to the beach deposits which suggest that the beach ridges are more resistant but this is not so. Farmers have done their best to restrict the river from eating at their land. The slow velocity of the river has helped them control its direction. The low velocity of the Petit Rhone is evident when one examines the bed load. It shows scarceness of coarse fluviatile sands present in the Grand Rhone (C. Kruit, 1955). The Petit Rhone may reach depths of 10 meters in places (C. Kruit, 1955).

(3) The ancient channels- There are two types:

The first group of ancient channels are those that were abruptly abandoned. Bras Mort was closed in 1559 and the Bras de Fer was closed in the begining of the 18^{th} century. Both of these channels are well preserved on the delta surface. The channels of this type are filled near their heads with crevasse and natural levee deposits from the new channel that robbed them. Bras Mort is dry, but Marais de l'Escale is swampy. Similarly, Bras de Fer is dry with levee deposits at the head, and is swampy further downstream. It also has a saline lake, the Vieux Rhone. After the Vieux Rhone channel was abandoned, its mouth (Grau de la Dent) was cut off by marine transported sediments and the small grau (opening) is artificially held open.

The second group consists of deteriorated channels, that is, they were not abruptly cut off but remained active after their prime and were able to gradually shrink in width with the lowering discharge. The Rhone de Peccais used to carry the main discharge when the Rhone d'Albaron was in its prime. When the Rhone d'Albaron deteriorated, the active channel became the Fourques channel, and after 1552 the Peccais channel slowly deteriorated in width from 120 meters to 10 meters (C. Kruit, 1955). In contrast, Bras Mort was cut off 400 years ago and it still has its width while the Rhone de Peccais has lost 9/10 of its width due to slow deterioration (C. Kruit, 1955). Some of the deteriorated channels are now used for irrigation and are termed "roubines" locally. If a channel deteriorates, Former channels (Rhone de St. Ferréol, Rhone d'Ulmet, and Rhone d'Albaron) are often preserved as narrow elongated marshy depressions in the center of a natural levee system. In uncultivated areas they remain recognizable.

Different successive stages of coastal accretion illustrating the growth and distruction of channels have been reconstructed from historical data (Russel, 1942), and from the physiographical study of C. Kruit (1955). They are represented as follows (Figure #8, page 34):

A. The sea reached approximately its present level after a rise which started at about -100 meters, at the end of the last period of glaciation. At that time the northernmost beach cordon, which is exposed on the present delta surface, faced the sea. The Rhone bifurcated near Villeneuve into the St. Ferréol and Ulmet channels (see Figure #7, page 31). The Plaine de la Crau was largely separated from the sea by a barrier beach, formed of older reworked beach deposits, and a narrow marshy lagoonal area. La Roque, a cliff of Cretaceous limestone, was an isolated island.

B. The delta was enlarged considerably in a southern direction by the accretion of numerous beaches, which together form an impressive beach pattern. The predominantly westward direction of marine transport prevented much accretion from taking place in the eastern part of the delta.

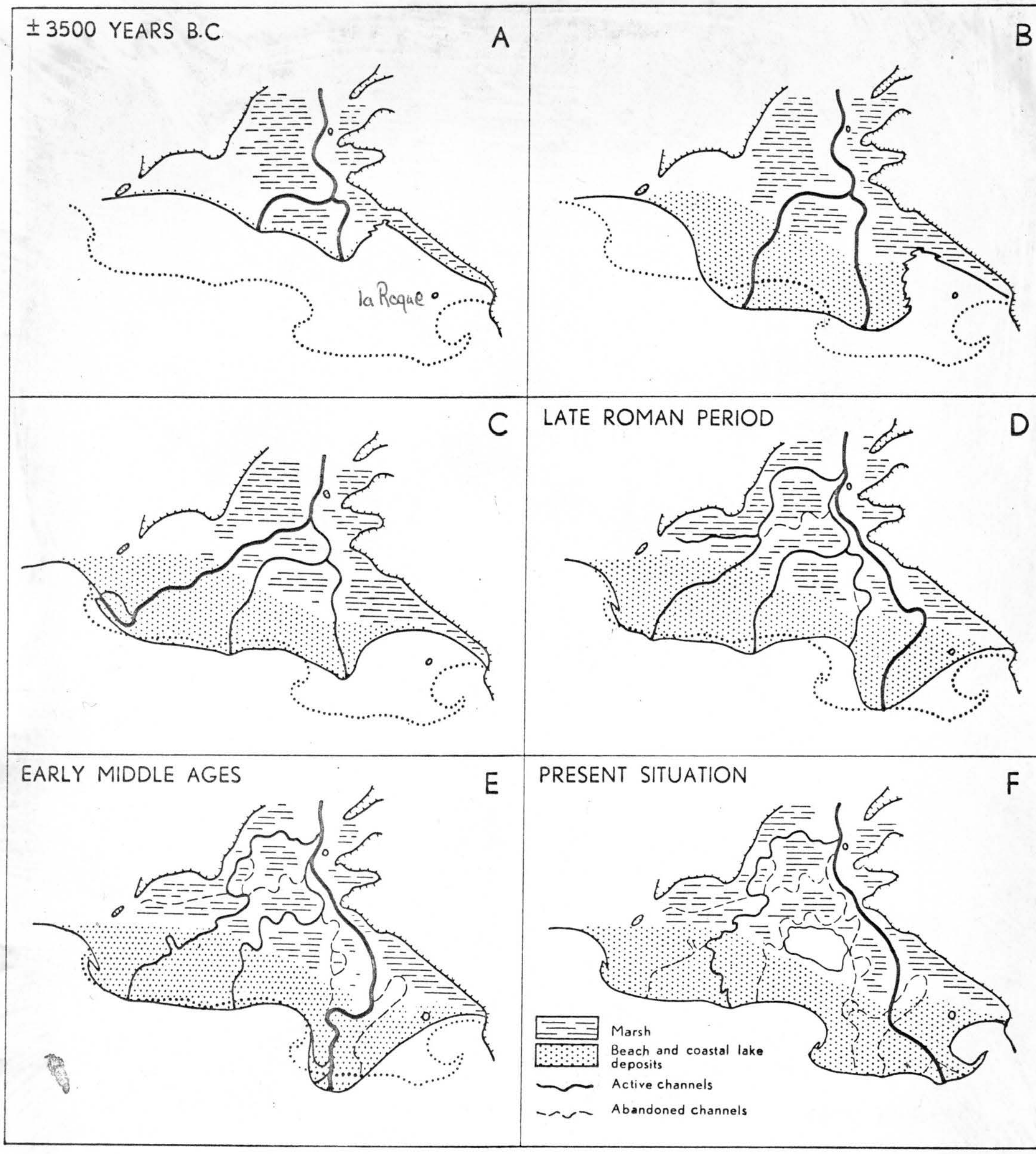


Figure #8 Delta advance as related to channel changes during the last 5,500 years (after C. Kruit, 1955).

C. The Rhone d'Albaron was formed. It found an outlet to the sea straight across the beach ridges near Sylvéréal. This new distributary carried away much of the discharge of the existing mouths of St. Ferréol and Ulmet, so that sediment supply to the sea decreased here and coastal erosion was initiated. The erosion products were carried westward and settled, together with abundant fresh sediment supplied by the Rhone d'Albaron, in the southwestern part of the delta. The natural levees of the Rhone distributaries were densely populated by Greek and Roman inhabitants successively.

D. Late Roman period. Much deforestation in the Rhone drainage basin caused greater maxima in the water discharge. This led to increasing crevassing activity, and important new channels were formed. The Petit Rhone broke into the western delta flank basins and returned into the Albaron channel near Albaron. From time to time the Tourradons crevasse supplied a surplus of the discharge into the southwestern flank basins, but it could never grow to the size os a distributary as its route to the sea was blocked; to the south by a broad area fo beach ridges, and to the west by a ridge of cemented gravels of Pliocene age which separated the southwestern flank basins from a lagoonal area (Etang de Mauguio). The Grand Rhone channel developed from a crevasse that broke into the eastern delta flank basins and found its way to the sea in the southeastern delta area. From this time onwards the Grand Rhone received the main discharge. This caused renewed active accretion of the southeastern part of the delta. La Roque became included in the delta deposits. The upstream part of the Rhone d'Albaron became blocked and silted up; in a later period the same happened with the Rhone d'Ulmet.

E. Early Middle Ages. Crevassing continued to be active and resulted in changes in the channel pattern which threatened the existence of important commercial routes. Stagna, the navigable route from the sea to St. Gilles through the western delta flank marshes (Figure #7, page 31), was shut off by a westward shift of part of the channel of the Petit Rhone. The Galéjon route deteriorated and silted up gradually, as a result of the movement of the Grand Rhone from Bras Mort to Bras de Fer.

F. The present situation. The deteriorated Rhone de St. Ferréol was shut off artificially in 1430, shortly after the final activity of the Rhone d'Ulmet. Etang de Vaccarès was transformed from a marshy area into a saline basin. The Rhone d'Orgon was cut by the inhabitants of Stes. Maries (1552), in order to provide this town with a supply of fresh water, which had ceased when the Rhone de St. Ferréol was blocked. The Grand Rhone has shifted its mouth again and now enters the sea near Port St. Louis, where a triangular piece of land has been added to the delta surface since 1711. Erosion attacked the coast near the former mouths of Bras de Fer and Bras Mort. The larger part of the erosion products was transported and redeposited near Pointe de Beauduc. The discharge of the Petit Rhone continues to be small; the coastal erosion of Petite Camargue and the accretion of Espiguette have continued. As far as possible, the stages have been dated from historical evidence. The construction of dikes largely prevents the supply of clastic sediments to the deltaic basins, so that at present non-depositional conditions prevail on the delta surface.

b) Point bars- A point bar is an area of deposition on the convex side of a meander loop. The surface of a point bar is characterized by a series of alternating arcuate ridges and depressions called swales. There is a good example of a point bar system inside Bras Mort. In Haute Camargue, the point bars have been leveled for agriculture but they are reflected in the boundaries of the land parcels. The sand dunes along the upper Petit Rhone are formed by wind modification of point bars. In point bar systems, coarse sands are found to be overlain by finer ones.

c) Natural levees- These are elevated areas which border channels, where deposition takes place whenever the channel water overflows it banks. Dikes, constructed to retain the discharge even during high floods, now prevent any deposition in the levee environment. Good sediment is available on the levees for farming and there are vineyards and rice plantations on them. The crest of the levees slopes to the coast and represents the gradient during flood stage. The natural levee crest gradient of the Petit and Grand Rhone is the for more than 20 km. after bifurcation (C. Kruit, 1955). The difference in the lower course should be attributed to the different lengths of the channels. The width of levees of the Rhone distributaries varies from 2 to 4 km. and the elevation above the adjacent basins decreases downstream from 4.5 to 1.0 meter (C. Kruit, 1955). After deforestation of the drainage area, accelerated deposition took place on the levees.

The natural levees show sediment sorting in a direction perpendicular to the channel. They grade from fine grained sands to silts and to clays, from the banks to the basins. Because of the short periods of flooding, the sorting is generally poor in detail but good when the whole levee deposit is considered. Where uncontaminated coarse sand exists on the levees, it has been wind blown (at times when water levels were low) from the channels and often forms dunes.

d) Crevasses- A crevasse is a secondary channel, cut in a natural levee, and during flooding it helps to disperse surplus discharge into the flood basins. Two types of distinctions can be made:

(1) Crevasse channels- Crevasse channels occur often on the outer bank of a river bend and they develop their own natural levees. An example of this is the Galéjon channel which cut in the outer bend of Bras Mort. South of Salin de Giraud there are several crevasse channels in the levees of the Grand Rhone. Many channels have been wiped out by leveling for rice paddies. If the basin in which the crevasse empties is well drained, such as delta

flank basins, the crevasse may develop into a distributary channel. The Rhone Delta has shown insignificant submergence and so the distributaries are shifted to the flanks by crevassing. The oldest distributaries, Ulmet and St. Ferreól, have been shifted in such a manner and are now the Grand Rhone and the Petit Rhone. The crevasse channels show sediments ranging from fine grained sands to silts. Because they are small scale distributaries, it is likely that one would find these grades in the channels. The crevasse channels show unusually good sorting, similar to marine deposits.

(2) Crevasse tongues- These are the downstream portions of crevasse deposits. A crevasse tongue is a low ridge pointing from the border of a natural levee into the adjacent basin. There are no traces of channels in tongues as observed by C. Kruit in the marshes of the northern basins. Good examples of crevasse tongues are in the Marais de Saliers. They are usually elevated 40 to 60 cm. and slope gently into the marsh (C. Kruit, 1955). The absence of tongues in the south is probably due to erosion subsequent to deposition. Since they are the extension of a crevasse, they are made up of fine silts and clays.

e) Fluvioaeolian dunes- These are dunes that have arisen from fluviatile deposits, mainly point bars. The dunes in the area of the Petit Rhone average 15 meters in height (C. Kruit, 1955). It is thought that when the discharge was low in the Rhone, at the time of birth of the Petit

Rhone, the sand of the Petit Rhone channel dried out and then the wind began transforming the point bars to dunes. These dunes contain coarse sands, the same grade as channel deposits.

f) Basins- There are two types, based on locality.

(1) Central basins- Central basins are enclosed by Recent deposits. In the north the basins (examples- Marais du Pont de Rousty, Marais de la Grand Mar) are completely enclosed by natural levee ridges and crevasses. In the coastal part of the delta, the central basins are bounded partly by ancient beaches such as to the south of Etang de Vaccarès. The northern basins and the southern ones near the Rhone distributaries are commonly reed marshes, due to the fresh to brackish water conditions. The marshy basins are approximately at sea level and contain fine silts and clays. There is little chance for erosion in the fresh water basins except for aeolian but the reeds growing in the reeds growing in the shallow parts curtail this possibility.

(2) Delta flank basins- The delta flank basins are bounded by Recent natural levee deposits and Pliocene and Pleistocene gravels that dip away under the delta deposits. The basins on the delta flank have provided better navigation in historic times because the Rhone channels have unstable sand bars in the outlets to the sea. The Romans dug a canal from Fos to Arles in 103-102 B.C. which decayed and was later reinforced. Now it is derelict and

the Canal St. Louis has served the mouth since 1871. The basin at St. Gilles was a salt water basin but the expansion of alluvial aprons cut the area off from the western lagoons and now the basin is a reed swamp (C. Kruit, 1955). The delta flank basins also contain fine silts and clays.

Now the coastal environments will be discussed.

a) Beaches- Sandy beaches are present along practically the entire shore and the larger part of them are slowly retreating. A few show rapid advance (Figure #9, page 41).

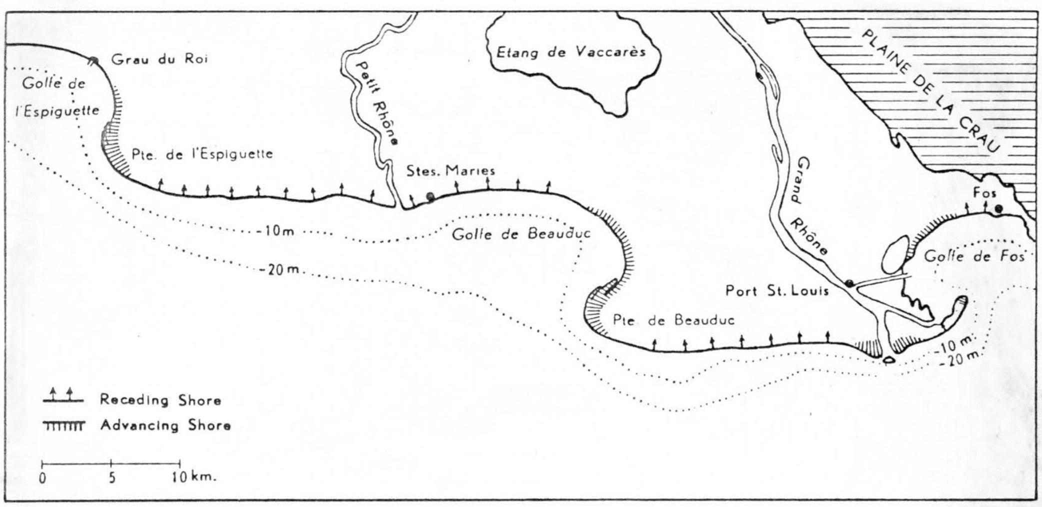


Figure #9 Advancing and receding shores of the Rhone delta (after C. Kruit, 1955).

The beaches of the receding shores are usually narrow (about 15 to 30 meters) so they can't contribute very much to stratigraphy. On the other hand, beaches of advancing shores are important for stratigraphy. The advance of the shore flanking the mouth of the Grand

Rhone is due to fluviatile supply while the advance of Pointe de l'Espiquette and Pointe de Geauduc is mainly due to the supply of marine sediments from retreating shores.

The beach sands are almost exclusively medium to coarse grained sands and only the protected areas show finer sands. It is suggested here that a relationship exists between the grain size and heavy mineral content of the beach sediments and the distance of deposition from active distributary channels. This will be investigated in a later paper. On the beaches, the sand above sea level is notably dry, while just inland toward the basins it is wet. The pH in the area is such that $CaCO_3$ is deposited and cements the sand, which is 70% quartz and 30% calcareous (Russel, 1942). Then the wind attacks and carves patterns where the strength of cementing varies (Photo #6, page 43).

During southeast storms the waves reach high points on dunes and leave a banding which is due to heavy minerals deposited (Douboul-Razavet, 1956). The sea transverses the dunes and flows into the basins and lagoons, and there fine silts and clays come out of suspension.

Near the mouth of the Grand Rhone, dark silts in crusty, flat layers about .5 cm. thick were present on the beach. They were very hard to break, presumably due to cementation. As the waves break in the littoral zone, a very fine layer of silt is left by one wave, only to be removed by the next. It is this author's conclusion that the thick, silty layers are deposited in low areas in the beach sand, where water collects as waves run up on the beach and then permeat the sand leaving the silt behind.

Just west of the Grau de Roustan on a retreating shore a steep slope of about 30 cm. is present at the waterline. The mistral blows sand towards the Mediterranean and the sea is constantly pushing the sand toward the beach. Together they builds these ridges (Photo #7, page 44).

Photo #6 Patterns in beach sand due to differential cementation by $CaCO_3$. Looking south from a point 1.5 km. east of Grau de Roustan.

Photo #7 Beach ridge at the waterline, looking west from a point 3 km. west of Grau de Roustan. Note the wind ripples which are perpendicular to the direction of the mistral.

(1) Beach accretion by fluviatile supply- The changes of the coast near the mouth of the Grand Rhone since 1841 are illustrated in Figure #10 (page 45). In 1841, three passes were present in the subdelta downstream from Tour St. Louis, a light house built in 1737. The Grau du Piémanson was closed to prevent fresh water from interfering with the salterns just west of it (Photo #8, page 46). The Grau de Roustan was closed when the Grau de Levant was modified by jetties: two dikes narrowed it towards the mouth in order to increase the velocity of the Rhone current. This would prevent the channel from silting up, and it could be used for navigation. At that time a submarine talus was formed in front of Grau de Levant.

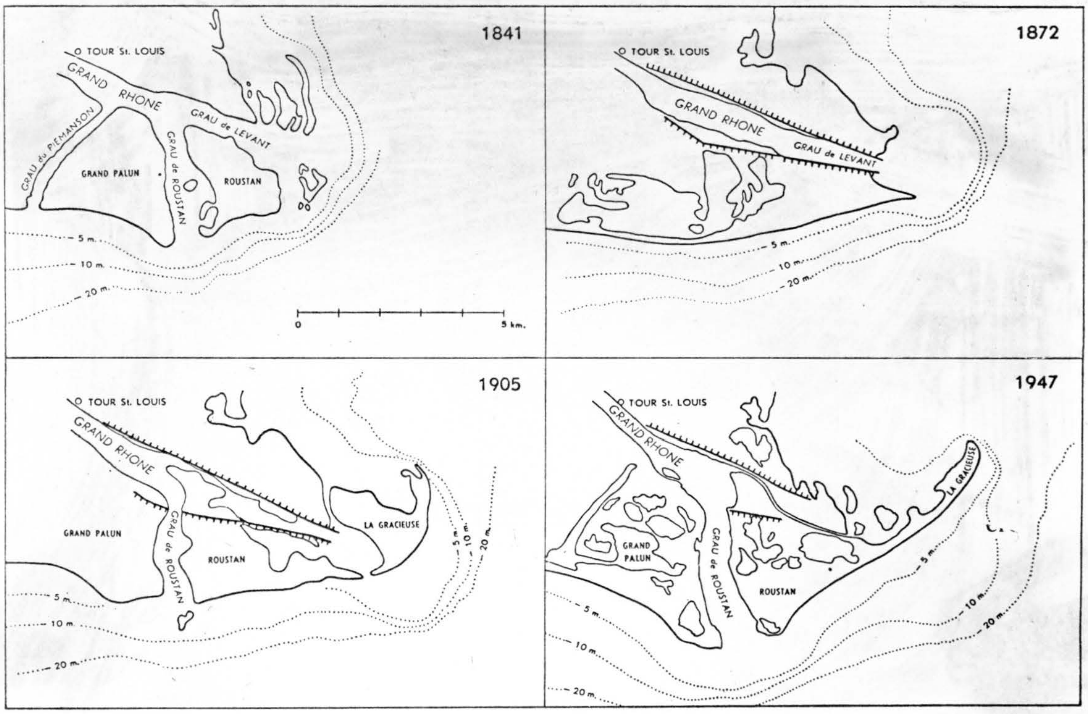


Figure #10 Development of the present mouth of the Grand Rhone since 1841 (after C. Kruit, 1955).

In 1905, a serious flood reopened the Grau de Roustan and it soon enlarged into the main pass. Grau de Levant deteriorated into a small channel that was better adapted to the breadth at the mouth of the jetties (Photo #9, page 46). A spit (La Gracieuse) was built in front of the former pass. The situation in 1947 shows that in 40 years the present mouth of the Grand Rhone has moved about 1 km. to the south. This extension has been brought about by accretion of short beach ridges that face the open sea at both sides of the mouth. The mechanism for the advance of the Rhone differs from that of the Mississippi. The Rhone grows by means of the emergence of beach cordons, whose presence persists on

Photo #8 Grau du Piémanson, looking southwest from the Grand Rhone. Note the salterns in the upper right.

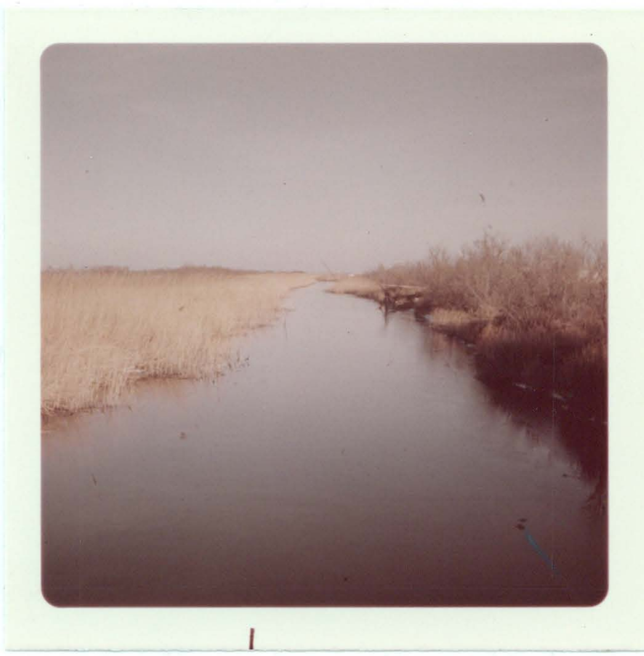


Photo #9 Grau de Levant, looking east from a point 1 km. west of its mouth. Note the typical fresh water reed growth.

much of the interior of the delta. These beach ridges converge at a distance of about 3 km. from the mouth of the Grand Rhone and together with the interlying swales, they have built up a subdelta consistion of two triangular plains, flanking the present mouth.

Islands are formed at the mouth of the Rhone when the shallow distributary mouth bars rise above sea level. As each island reflects the flow of the river, it is eroded to the shape of a triangle which points upstream (Duboul-Razavet, 1956). The islands are either eroded below sea level, or they are joined to the delta by the action of the mistral, which is accompanied by the erosion of the east side of the river mouth. This explains the eastern migration of the Grau de Roustan. Duboul-Razavet (1956) also points out that boat wrecks aren't determinate in the formation of the islands. This opinion is contrary to others who feel that wrecks cause islands to rise from shallow sand bars. Duboul-Razavet feels that rising islands cause wrecks.

The beaches that flank the mouth of the Petit Rhone project about 400 meters south of the average position of the coastline, around the area of Stes. Maries (C. Kruit, 1955). The characteristic abandoned beaches, present at the mouth of the Grand Rhone, are absent here due to coastal recession. The sediment supply of the Petit Rhone is too small to initiate coastal accretion and only serves to retard the effects of erosion. The beaches on either side of the Grau d'Orgon have lumps of mud exposed on the sand. They are the remains of ancient lagoons, progressively destroyed by the sea (Duboul-Razavet, 1956).

(2) Beach accretion by marine supply- Sediment is transported westward along the delta due to waves produced by southeastern winds. Along with the swash and backwash of the waves, westward longshore currents have been recorded. At Pointe de Beauduc and Pointe de l'Espiquette, westward currents deposit sediments in wave built ridges parallel to the shoreline. They grow and eventually rise above sea level. At Pointe de Beauduc, a series of spits originated in this way and they are expanding to the northeast. They are supplied from the retreating shores to the east. The coast of Faraman loses over twice as much sediment per year as the Rhone transports (Repelin, 1914). Linear lagoons form between the ridges and are ultimately filled, becoming salt flats. A slow counter current along the shore of the Golfe de Beauduc has transported some sediments from the northern shore to the southeast and created a small spit in front of Grau de Calabert which deviated the mouth of this tide gully to the south (C. Kruit, 1955). The accretion of Pointe de l'Espiquette is similar but the counter current is apparently absent from here (C. Kruit, 1955).

East of the mouth of the Grand Rhone a longshore current has been the cause of the large spit (They de la Gracieuse) present at the entrance to the Golfe de Fos.

As previously stated, an eastward current is possible here due to the relationship between the coast and the direction of the dominant onshore wind.

There were two spits on the north shore of the Golfe de Fos. One had moved the mouth of the Canal de Galéjon about 1.5 km. to the south. The other spit diverted the mouth of the tide gully connecting Etang de Gloria with the Golfe de Fos in a southward direction. Both of these spits have been destroyed by the present construction in the gulf. This will be discussed later.

The orientation of the two points (Pointe de Beauduc and Pointe de l'Espiquette) is particularily favorable for the growth of dune systems elongated by the dominant wind, the mistral. It picks up sand and forms transverse dunes which move south and gradually break up into longitudinal dunes along the beach, gradually diminishing eastward.

b) Abandoned coastal ridges- There are many sand ridges which indicate abandoned beaches on the delta. It is difficult to tell between beach and dune ridges so they are collectively called coastal ridges. The northern most ridge is the Sylvé Godesque. This ridge stands about 1 to 2 meters above sea level (C. Kruit, 1955). It was wooded but is now used for vineyards. The oldest superficial ridge west of the Grand Rhone is the eastern extension of Sylvé Godesque called Ile de Mornes which stands about 1 meter above sea level (C. Kruit, 1955).

It is being cut away by waves from Etang de Vaccarès. Bois de Rièges is slightly higher and is the only ridge still wooded in the area. Trees can grow there either because a pocket of fresh water exists or the salt water is not able to seep high enough to interfere with the roots. The ridge has been raised by aeolian supply which effects southward movement. Bois de Rièges has also been eroded by waves on the northern side. There are ridges further south but they are hard to find because the upper portions have been reworked by the currents and waves of the saline lakes.

To the southwest of the youngest ridge of Sylvé Godesque is a composite series of beach and dune ridges on which the Mas de la Pinède is located. This system ends in a series of spits that never reached Sylvé Godesque. Their pattern is an excellent indication of the growth direction of the delta in that area, and is very similar to the present development of Pointe de Beauduc and Pointe de l'Espiquette. The construction of the system probably ended with the birth of the Sylvéréal channel (C. Kruit, 1955). The channel originally turned northwest behind the youngest beach deposits and it is well preserved. The Sylvéréal channel later cut straight through the coastal ridge and silted up the "Gulf of Sylvéréal" (C. Kruit, 1955).

When the Rhone d'Albaron took over the main discharge from the Rhone St. Ferréol, that area decreased and sent much sediment to the mouth of the Rhone d'Albaron. Spits formed which were often cut through but suceeded in diverting the mouth westward as indicated by Rhone Mort and Rhone de St. Roman. All of these ridges, young and old, converge south of the Etang de Mauguio which seems to mean that this has been a stable shoreline for some time.

To the east of the Grand Rhone the oldest abandoned ridge is near Mas Laget. It is difficult to say if it is the eastern extension of Sylvé Godesque or not.

The former mouth of the Rhone d'Ulmet is just south of Les Salines and the ridges show morphological similarity to the present mouth of the Grand Rhone. The eastern part of the ridges has been destroyed by the western migration of Bras de Fer.

Originally Port St. Louis was a light house (1737-1740) erected on a coastal redge one kilometer north of La Palissade. The light house is still standing and is a good reference point from which to base accretion of the Grand Rhone mouth. The abandoned ridge on the right bank of the Rhone at Port St. Louis was formed after 1711 when the Rhone left its Bras de Fer course and since then about 25 km^2. has been added to the delta, southeast of Port St. Louis.

One kilometer north of Port St. Louis are the beach ridges of the original Grand Rhone channel which produced Bras Mort in its final stages. It debouched near Grau d'Enfer.

The ridges show the same grade size as the active beaches, that of medium to coarse sand (C. Kruit, 1955). By studying the sediment size of abandoned coastal ridges it is possible to tell if they were protected areas or not. If they were, they should show finer sands than if exposed to the full strength of the waves.

c) Coastal basins- There are two types:

(1) Lagoons- They are flooded basins that have a permanent connection with the sea, and are separated from it by a spit or sand bar which protects the lagoon from the surf. Etang de Gloria was a lagoon in the Golfe de Fos but it is now filled in with sediment from the construction in the gulf. There is a lagoon at Pointe de Beauduc, where a lighthouse has been built between two abandoned ridges. Near Pointe de l'Espiquette only a small lagoon is present.

(2) Coastal lakes (Etangs)- Coastal lakes are permanently flooded depressions between coastal ridges which are not directly in contact with the sea. Most coastal lakes are cut off lagoons, others are abruptly closed Rhone channels and passes. Active beach growth on the Rhone delta has caused the coastal lakes to outnumber the lagoons. The predominance of sandy deposits in the coastal area permits ground water circulation, keeping the deeper coastal basins permanently flooded with salt water, even in summer. The basins are gradually filled with erosion products from abandoned coastal and fluviatile ridges. Before dikes were built, the crevasses helped move sediment to the basins.

When a lake is filled with sediment approximately to sea level, it may dry up in summer and become a saline flat. Saline flats are coastal lakes that are only temporarily flooded. Mud cracks form on the surface and the silts and clays become plastic and feel like leather.

South of Etang de Vaccarès there is a low dike which prevents the sea from flooding during southeast storms. Here it has been shown that uncontrolled saline basins tend to gradually increase in size as a result of eroding their shores. The former beach ridges have almost been destroyed. The Petite Camargue is morphologically similar but younger.

The coastal basins were formed by beach sands but since have been filled with fluviatile muds and marine muds. Salicornia grows in coastal basins and other salt environments. Photo #10 (page 53) shows that plant.

Photo #10 A temporarily flooded basin and a permanently flooded one. Note the typical salt environment plant, Salicornia. Looking northeast from a point 2 km. east of Grau de la Dent. Phare de Faraman is in the background on an abandoned coastal ridge.

Photo #11 A rarely flooded basin near Etang de Fournelet showing the same Salicornia plant. Note the cattle in the center of the picture. There are cattle ranchers further north on the delta especially in Haute Camargue.

d) Submarine delta slope- The submarine delta slope extends from the present shoreline of the Rhone delta to where the Recent sediments meet the continental shelf (Figure #12, page 55). The most gradual slopes exist off areas undergoing erosion such as off the coast of the Petite Camargue, where the submarine delta slope averages 3 to 4 meters per kilometer. The sloping muddy bottom here merges in the basal part with the horizontal shelf. The sediments of the shelf are sandy (Figure #11, page 55). Off the mouth of the Grand Rhone, the is about 17.5 m./km. with a maximum of 35 m./km. (C. Kruit, 1955). The youngest deltaic advance usually has the steepest slopes. Much of the sediment of the Grand Rhone has traveled west

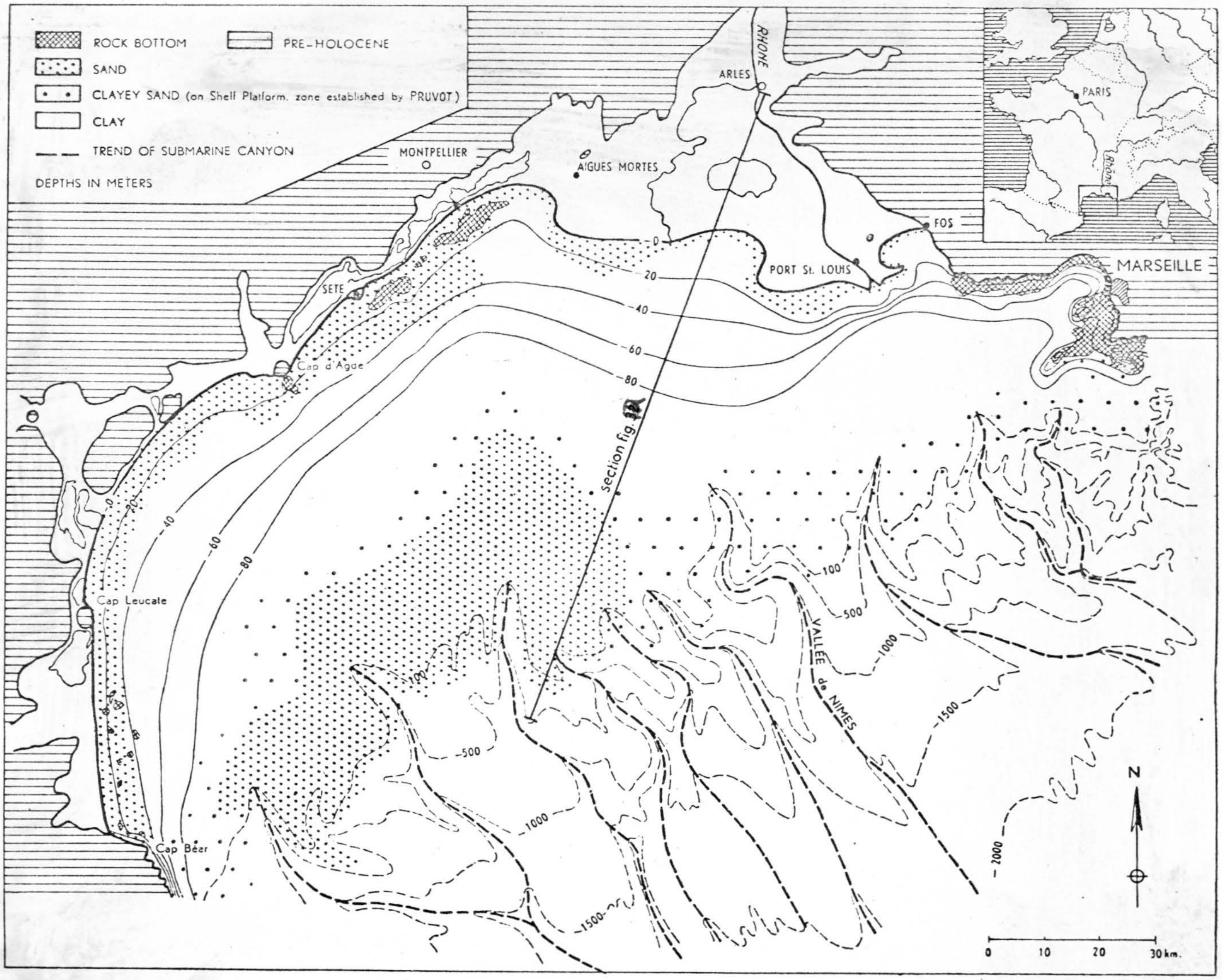


Figure #11 The Golfe du Lion
(after C. Kruit, 1955)

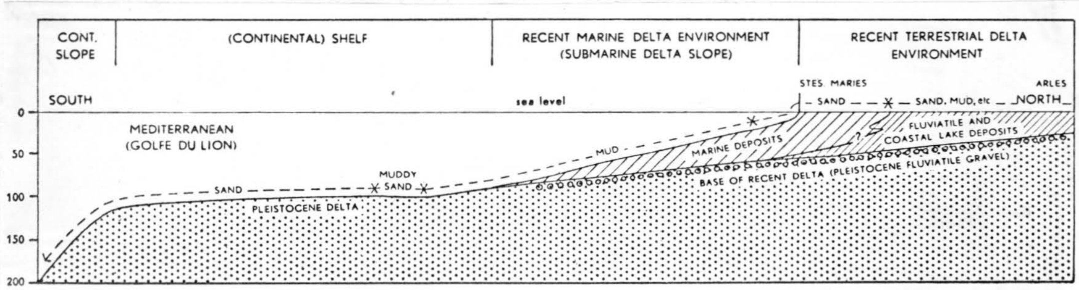


Figure #12 Section through the
Recent delta deposits (after C.
Kruit, 1955)

of the Grau de Roustan. The same is true for the Nile delta. The relatively stable coasts are intermediate in slope.

Off unprotected beaches the depth of erosion is 10 to 15 meters and off protected beaches it is less than 10 meters (C. Kruit, 1955). The north coast of the Golfe de Fos is a protected beach, and before the construction began, a broad beach plain would emerge when the mistral was strong.

There are three types of sedimentary environments on the submarine delta slope:

(1) Fluviomarine environment- The fluviomarine environment is near the river mouth and is characterized by rapid deposition of sediment. The sediment here is poorly sorted and the clay content is usually high. Rapid deposition results in a quick expansion of the subdelta. Another consequence of rapid deposition is that waves cannot find time to midify the fluviatile aspect by sorting. Off the mouth of the Grand Rhone, there are coarse fluviatile sands and in deeper waters they are mixed with greater quantities of silts and muds. The muds can be called marine (C. Kruit, 1955) (Figure #13, page 57). The influence of the annual variations of the discharge of the Grand Rhone on the distribution of grain size types in the area of rapid deposition is unknown.

(2) Purely marine environment- The coarse sediments are better sorted than similar fluviatile deposits. A definite correlation exists between the size of sediments and the

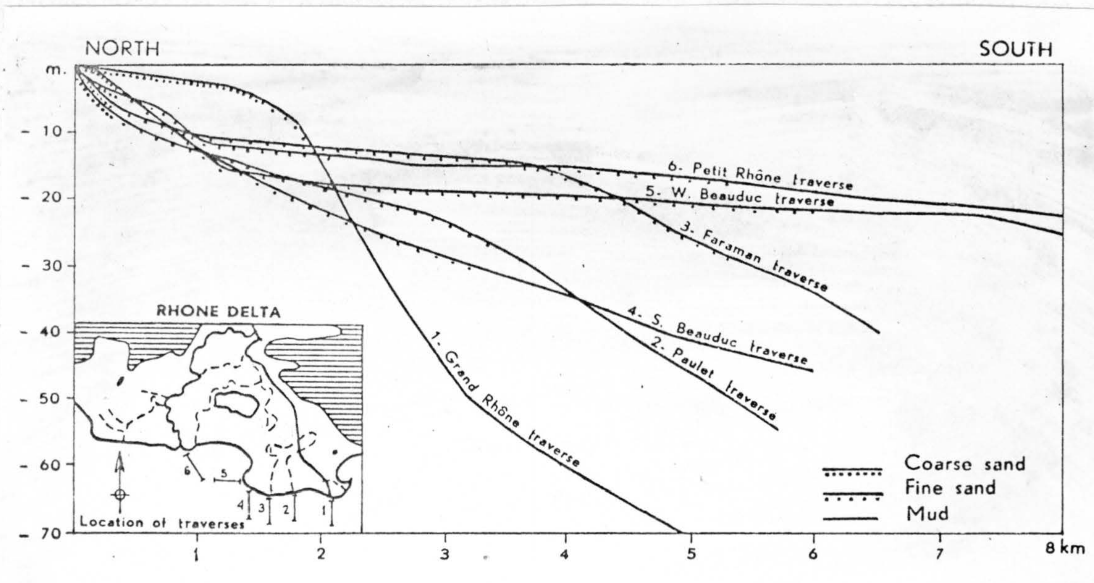


Figure #13 Sections of the submarine slope of the Rhone delta (after C. Kruit, 1955).

depth of deposition, which illustrates the effects of currents on sorting. Coarse sands only occur on beaches. Finer sands are present to depths of about 20 meters and then silts and clays dominate (Figure #13, West Beauduc traverse).

(3) Bay environment- The sediments in the Golfe de Fos show less regular relationships than do sediments of other marine environments. Fluviatile and marine size sediments are both present. Fluviatile sediments are present off the old mouth (Grau de Levant), and were most likely deposited when that channel was active. There is a fan of sediment spreading out from the tip of They de la Gracieuse that has decreasing grain size in a northeast direction (C. Kruit, 1955). The present dredging in the Golfe de Fos has surely disturbed the sediment enough to make that area unsuitable for futher research.

e) Continental shelf to the deep sea fan- The surface of the southern part of the continental shelf is at a depth of 100 meters. Worldwide evidence suggests that there was a drop in sea level of about 100 meters during the last Pleistocene glaciation. The shelf is bounded on the south by a steep continental slope which extends in an approximate straight line from Cap Bear to Marseille. From the investigations of Boucart (1950), it is apparent that the continental margin slopes less steeply off the Golfe du Lion than to the and west where the continental margin coincides with the present coastline.

There are a number of submarine canyons on the continental margin which flow into deltaic lobes at a depth of about 2000 meters (Figure #11, page 55). Two large submarine canyons cut into the continental shelf directly south of the mouth of the Rhone (Menard, 1965). These canyons grade into channels which hook sharply to the left until they trend along the base of the continental slope. Menard feels that this left hook is due to the Coriolis force which affects turbidity flows. A core taken on the deep sea fan at the base of the slope had a heavy mineral suite typical of those from the Grand Rhone (van Andel, 1955, made an investigation of the heavy mineral suite of the Rhone delta), which indicates the fact that the outermost extent of the continental margin is influenced by Rhone sediments (Menard, 1965). The deep sea fan extends approximately 200 km. south of the Grau de Roustan (Menard, 1965).

Extension dans le Golfe de Fos

An American company, Atlantic, Gulf and Pacific, is dredging a path so large ships can enter the Golfe de Fos and transfer their cargo. This will be an annex port for Marseille. Bauxite from Australia is already present on the docks. The average depth of dredging is 23 meters and the sediment is used to fill the basins and lakes in the area (Etang de Gloria, Etang de la Roque) for future highways and loading docks. Not all sediment is transfered inland, some is disposed at sea or in the gulf where docks are being built. Straw is mixed with the dumped sediment (on the delta surface) to prevent wind erosion. The dredging of the channel into the gulf must be continued because the marine transport of sediment would quickly fill it in again. The gravel, which underlies Recent sediments, has been dredged up from the gulf and is being dumped on the beach (Photo #12, page 60). This gravel consists of semi-cemented rounded pebbles in a sandy matrix and is locally called "pudding."

The docks pictured (on the map) off the They de la Gracieuse have not yet been contracted. When this construction is finished it will be a sediment trap, unless the French government has the foresight to plan otherwise. Since 1964, 12 barges have been towed to the tip of They de la Gracieuse and left there to prevent sediment from moving into the gulf but they have all been covered by the Rhone's sediment load except for one.

Concrete walls are being built to protect the shoreline in the Golfe de Fos.

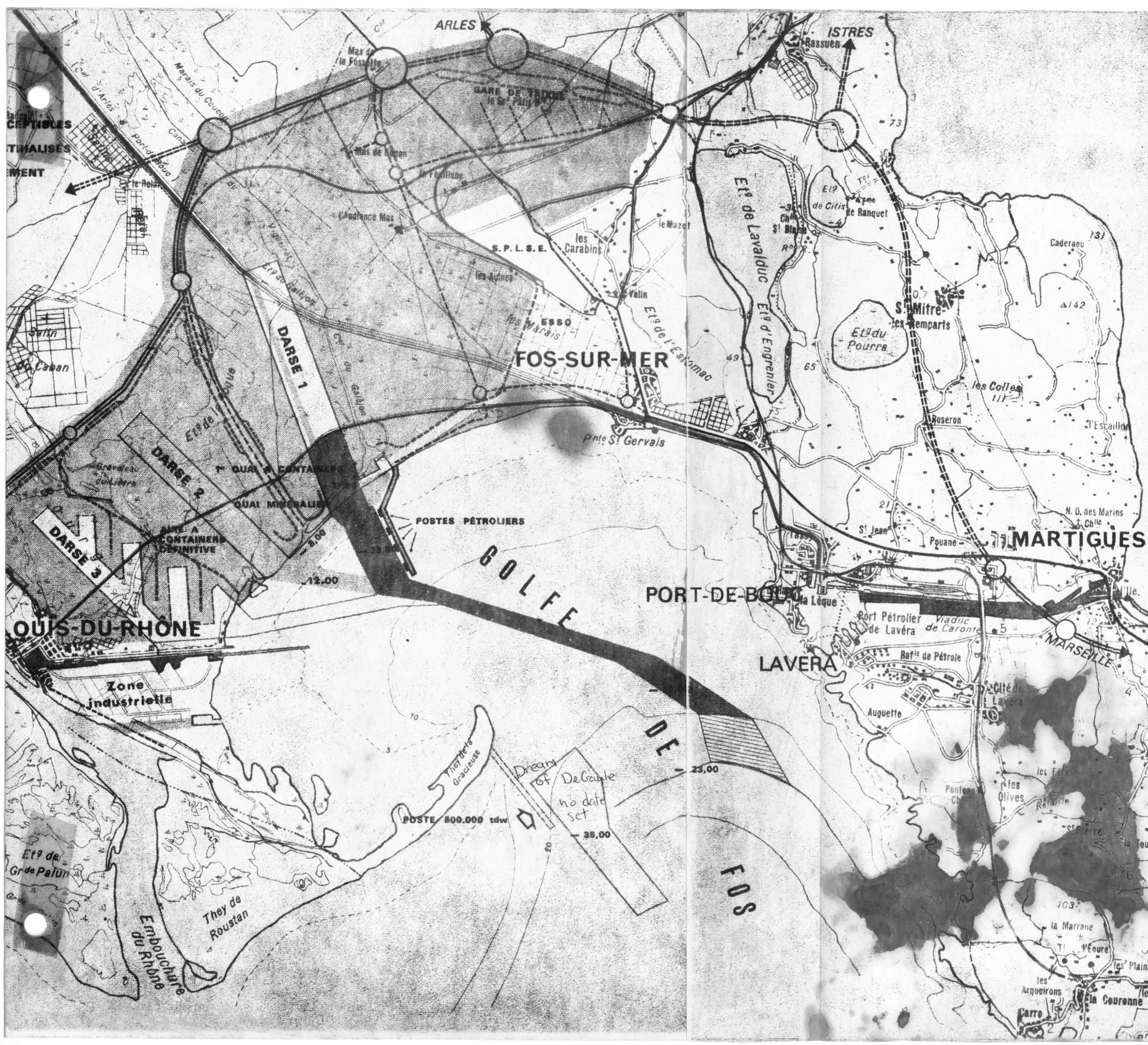
The French hope to finish this project in 10 years.

Photo #12 Gravels dredged from
the Golfe de Fos.

Management of the Rhone

In 1919, the Compagnie Nationale du Rhone was created for the following purposes: promoting navigation, production of hydroelectric power, and to aid irrigation. The plan is to build a series of dams and factories which will service the Rhone valley from Switzerland to the sea (Figure #14, page 61). The first dam completed was Génissiat which was put into service in 1949. Since then the following managements have been completed: Donzère-Mondragon in 1952, Montélimar in 1957, Baix-le Logis Neuf in 1960, Beauchastel in 1963, and Pierre-Bénite in 1966. The company plans to have all the managements on the lower Rhone (Lyon to the sea) completed by 1976.

There has been some question as to the affect of the dams on the normal supply of sediment that is carried to the delta. The river silts up the dams and dredging is necessary. When the river is dredged, most of the sediment is dumped further downstream past the dam. The Compagnie Nationale du Rhone has made studies of



PORT AUTONOME DE MARSEILLE

EXTENSION DANS LE GOLFE DE FOS

LEGENDE

ROUTES — EXISTANTES / EN PROJET

AUTOROUTES EN CONSTRUCTION

AUTOROUTES EN PROJET

VOIES NAVIGABLES CHENAUX ET DARSES — EXISTANTS / EN PROJET

VOIES FERRÉES — EXISTANTES OU EN CONSTRUCTION / EN PROJET

E C H E L L E

0 Km 1 2 3 4 5 Km

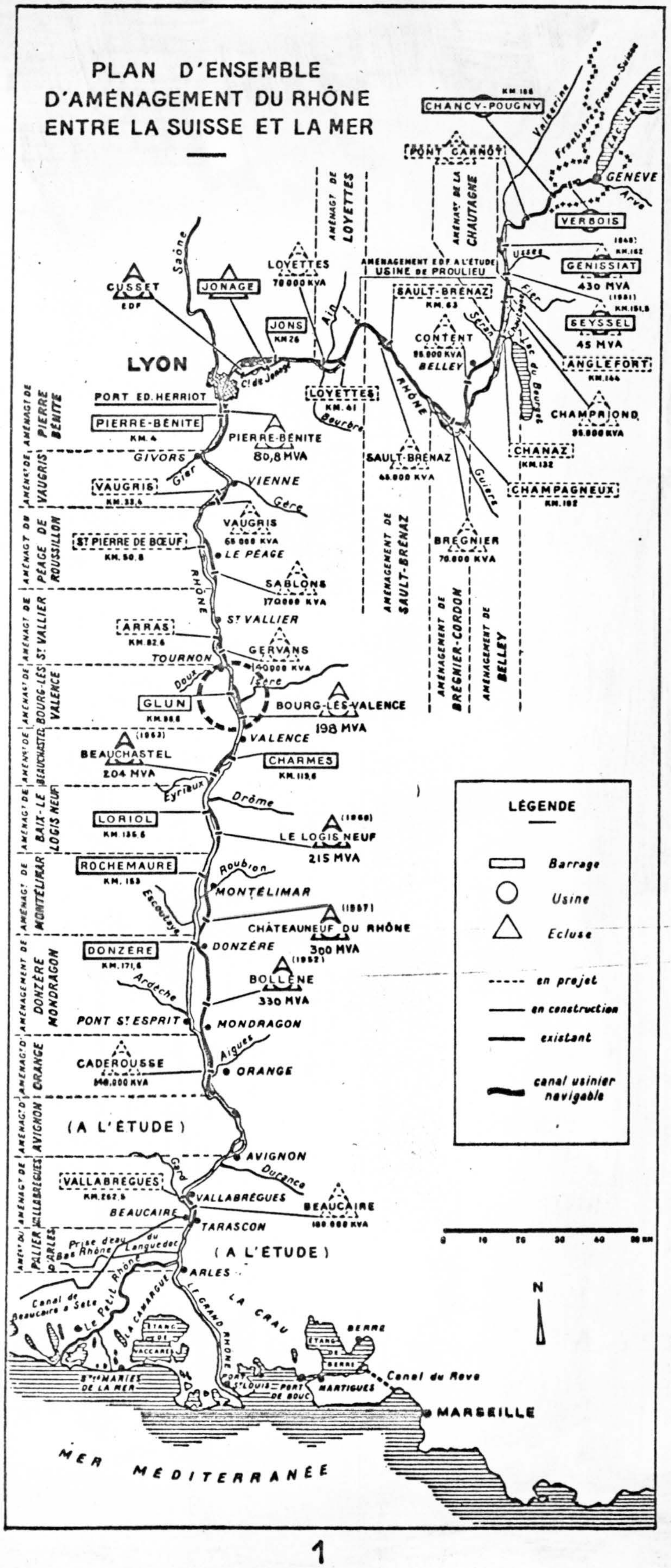


Figure #14 Plan for the management of the Rhone from Switzerland to the sea (project of the Compagnie Nationale du Rhone).

channel speeds necessary to move the sediment and they claim that all the sediment eventually reaches the sea (Savey and Deleglise, 1967). They say that during most of the year deposits are forming along the Rhone behind the dams, but when there is a flood the dams are partially opened and the sediment is reabsorbed and carried to the sea. Along with the dams are canals connecting the factories which are navigable and permit some sediment to bypass the dams. Mr. Boniface (personal communication) said that the same amount of water passes as before the dams were built, but it is more regulated now. Also, Faucher (1968) says that the series of dams has succeeded in making the river quiet and now permit year around navigation. So it seems as if the Compagnie Nationale du Rhone is accomplishing what it set out to do. However, Mr. Izaute of the Port Autonome (company in charge of the construction in the Golfe de Fos) thinks that because the dams regulate the flow of the Rhone, they have caused less sediment to be deposited off the delta front in times of flood. The Port Autonome has made measurements of the amount of sediment present at the mouth of the Rhone since 1934 and here are their findings. From 1934 to 1954 the amount of sediment constantly increased to 7,231,000 m^3 in 1954. From 1954 to 1962, the amount continued to increase to 12,353,000 m^3. However, from 1962 to 1963 the amount dropped for the first time to 12,149,400 m^3. No more measurements were made after 1963. It is difficult to say what this means, but Mr. Izaute suggests that the loss could easily be due to the calmer water silting up the dams upstream. After reading several articles and talking to engineers that are concerned with the project, it is this authors feeling that the spasmodic dumping of dredged sediment and the other periodic releases may cause changes in the mouth of the river since the times of tremendous sedimentation are now regulated. Wave action may now be able to keep up with the more even supply of sediment rather than having to face the annual flood load of the river. It will take more time before the effects are obvious.

In 1966, a dam was built on the Durance River, which diverted the river to Etang de Berre. This dam is not a part of the management of the Compagnie Nationale du Rhone, but it is worth considering. The Durance used to flow into the Rhone south of Avignon. It is a torrential river a indicated by the differences in discharge: 1,906 $ft.^3$/sec. minimum, 12,260 $ft.^3$/sec. average, and 326,000 $ft.^3$/sec. maximum (Reclus, undated). The lower course of the Durance is braided due to an oversupply of coarse material, chiefly gravels (Reclus, undated). Reclus also points out that in times of flood it may carry more water than all of the other streams in France combined. Since this river was diverted such a short time ago, it is hard to say just how the change will affect the delta, but the effect won't be negligible.

Vocabulary

automoteur- self propelling boat

autoroutes en construction- roads under construction

barrage- dam

chenaux- channels

dans- in

darses- docks

de, du, des, d'- of

écluse- lock, floodgate

en projet- in planning stage

étang- lake

golfe- gulf

grand- big

ile- island

le, la, les, l'- the

marais- marsh, swamp

mas- house, farm

ou- or

petit- small

phare- lighthouse

plaine- plain

route- road

salin- salty, saline

salinière- relating to salt production

usine- factory

voies navigables- ways navigable

voies ferrées- railways

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